Dynamics and Transport of the Indonesian Throughflow

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LONG TERM GOAL

The long term goal of this project is to identify the importance of the Indonesian throughflow to the global heat and freshwater balance. While the emphasis has been on climate related issues, the work is also intended to understand the dynamics of the exchange between the Pacific and Indian Oceans through the complex series of basins and straits that comprises the Indonesian archipelago.

SCIENTIFIC OBJECTIVES

The primary objective of this program is to estimate the temporal variability in the volume, heat and freshwater transport of water in the Indonesian throughflow region plus the associated errors. Specifically we wish to:

(1) Use cross-strait geostrophic calculations to determine fluctuations in the near-surface transport observed by a network of subsurface pressure sensors in the principal “outflow” straits of the throughflow as it leaves the interior Indonesian seas and enters the Indian Ocean. This involves (a) Identifying the dominant time-scales of the throughflow and the relative contributions of intra-seasonal, seasonal, semi-annual and annual frequencies in the near-surface transport; (b) Identifying the relative importance of the various straits that comprise the outflow passages in terms of the fluctuating volume and property transports.

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(2) Identify fluctuations in heat and salt associated with the near surface transport from direct measurements of temperature and conductivity associated with the shallow pressure gauge array, and from underway ADCP/CTD surveys of the region.

(3) Connect the near-surface geostrophic transport of volume and properties of the throughflow from the shallow pressure gauge pairs to independent measures of the total throughflow from historical and concurrent observations, in order to estimate the total depth-integrated transport.

(4) Understand the dynamical relationships within the Indonesian seas between observed fluctuations in near-surface transport and possible forcing mechanisms, such as local and non-local wind-forcing, over time scales from intra-seasonal to annual.

APPROACH

This grant was awarded to complete the fieldwork for the shallow pressure array within the Indonesian seas, and to analyse the data from that array in the context of the larger suite of related, simultaneous measurements. The general approach is to connect the near surface fluctuations in transport measured by the pressure sensors, with the vertical velocity and shear information from various moorings (past and present) within the same passages as the gauges, XBT data, and the ADCP/CTD surveys conducted during the deployment and turn-around cruises, to obtain the total transport through the passages.

The work represents a collaborative effort by scientists in the United States (Janet Sprintall, SIO and Werner Morawitz, Susan Hautala, UW), Australia (Nan Bray, CSIRO) and Indonesia (BPPT). Sprintall and Morawitz, along with support staff from SIO and BPPT, led the turn-around cruise of the pressure gauges in March-April 1998 from the Indonesian research vessel Baruna Jaya IV. Sprintall's contribution has primarily involved analysis of the pressure gauge array and the complementary data sets, with Bray and Morawitz. In late 1997, Bray accepted a position as Chief of CSIRO Division of Marine Research. Bray continues to contribute to the project on a nominal scientific basis, and provides an important link to maintain collaboration with Australian CSIRO colleagues. We have continued joint analyses with Gary Meyers and Susan Wijffels (CSIRO) of the XBT and WOCE hydrographic sections in the region; with George Cresswell (CSIRO) on the ASEAN mooring data; and with Michele Fieux and Robert Molcard (LODYC) on the mooring and hydrographic sections from the French JADE program.

WORK COMPLETED

Nine shallow pressure gauges, equipped with temperature and conductivity sensors, were deployed in the principal Indonesian outflow straits in December 1995. Eight of these gauges were successfully redeployed with 100% data recovery in March 1997, and again during this funding period in April 1998 from Indonesian research vessels. The ninth gauge (Ashmore Reef) is on an asynchronous deployment schedule and was turned around in June 1996 and August 1997. Sensor failure resulted in a data gap in the Ashmore location from November 1996 to August 1997. The entire network is due to be recovered in early 1999 unless additional funding can be secured to maintain it. The 28 months of pressure, temperature, and salinity time series are all of high quality, with the exception of the South Sumba salinity time-series which suffered from biological fouling. Additional measurements include

towed and shipboard repeat ADCP and underway CTD surveys taken across the minor and major outflow straits during the deployment and turn-around cruises.

Analysis during this funding period has concentrated on studying the various time-scales that are evident in the pressure gauge data, understanding the dominant processes involved, and quantifying and characterising their impact on the properties and transport of the throughflow. We have also continued to examine the validation of the geostrophic assumption in relating the pressure differences to velocity; “levelling” of the pressure gauges; and extrapolating the surface velocity to upper layer transport. Efforts have resulted in one publication [Bray et al., 1997] and one paper which has been recently submitted to Nature [Chong et al., 1998].

Another important part of this award is associated with the technical training of Indonesian scientists and colleagues from BPPT to enable scientific research within Indonesian waters. In April 1998 a delegation from BPPT that included the Director, Dr. Indroyono Soesilo, and the Head of the Baruna Jaya Research Fleet, Mr. Basri Gani, visited SIO to discuss and implement the details of the training program. The scope of material covered included fostering cooperation and expediting the exchange of data and resources between SIO and BPPT, and the analysis of the shallow pressure gauge array data within Indonesian internal seas. As a result, in October 1998 Mr. Kemal Sinatra received training in the area of research vessel management at the Scripps MarFac shipping facility, and Mr. Fadli Syamsudin received training at SIO with Sprintall on scientific processing of the Indonesian shallow pressure gauge array data.

RESULTS

The data from the pressure gauge array provide the first measurements of surface geostrophic transport variations through the primary straits and passages linking the Indonesian Seas to the Indian Ocean. Transport fluctuations through the straits are calculated assuming geostrophy to relate the cross-strait pressure differences to velocity (Figure 1; Chong et al., 1998). There is much evidence to support the geostrophic assumption. Average surface velocity inferred from the pressure gauges compared to along-strait current meter velocities at 20 m near the center of Ombai Strait, are reasonably well correlated. Differences between the two are expected; pressure differences reflect the average geostrophic velocity, while current meters measure velocity at a single point and include ageostrophic components. Additionally, in both Lombok and Ombai Straits, the change in average surface along-strait velocities from ADCP surveys between the 1995, 1997 and 1998 cruises are in reasonable agreement with the changes in the cross-strait pressure difference.

The pressure data are sufficient to infer shallow geostrophic transport fluctuations relative to a temporal mean. However, their exact vertical displacements with respect to the geoid are unknown, and to determine total transport we need to “level” the gauges, (i.e., determine the mean). This is acheived by connecting the relative transport fluctuations measured by the pressure sensors with the absolute velocity measured simultaneously by the ADCP surveys and current meters. We have begun this process in Lombok and Ombai Straits. In Figure 1 geostrophic transport was estimated assuming an exponential decay in transport with a depth scale of 62 m. The rationale here is that 80% of the ITF is in the upper 200 m [Meyers et al., 1995]. Future estimates will use the current meter data in each of the three main throughflow pathways (Lombok, Ombai and Timor), along with lateral information from our ADCP surveys, to determine the relationship between vertical flow structure and surface velocity.

The partition among frequency bands observed in upper layer transport from the various straits spanned by the pressure gauge array is complex (Figure 1). While transport through Lombok, Savu and Sumba Straits have a maximum during the south-east monsoon, Ombai Strait has no clear annual cycle. Semi-annual energy is apparent in Lombok and Sumba Straits but not in Ombai or Savu. The intraseasonal energy is strongest in Lombok Strait, decaying in amplitude from west to east, and apparently does not penetrate across the southern Savu Sea to Timor Passage. In fact, the spectrum of Timor Passage is surprisingly white, although this is probably due to the short record length in this passage.

The intraseasonal energy has been emerging as a pervasive feature in our pressure gauge data, and also in other measurements within the Indo-Australian basin (IAB). Much progress has already been made toward identifying sources of the intraseasonal energy. In the Bali pressure gauge, intraseasonal variations are most striking during December to May. Along the IAB northern boundary there is a 2.5 m/s eastward propagation of 60-day energy in the pressure gauge data, commensurate with a Kelvin wave speed of 2.4 m/s at these latitudes. Using daily-averaged ECMWF wind stress data, intraseasonal westerly wind burst activity was identified both along the equator between 80°-90°E (where events occur 30-50 days apart), and along the archipelago (30-90 days apart). The magnitude of the wind bursts vary with season: along the equator they are strongest during May to September while along the archipelago they are strongest during December to May. Kelvin waves generated by equatorial wind bursts at 80°E should reach Bali in only 30 days. Qualitatively then, the increases in sea level at the Bali pressure gauge correlate best with local wind. Potential remote wind forcing from equatorial regions farther west than 80°E have not yet been examined. Data from the pressure gauge array suggests decay of the 60-day energy east of Lombok Strait, consistent with the declining importance of the equatorial Indian Ocean source moving eastward along the islands [Qiu et al., 1998].

Intraseasonal variability is also evident in recent observations within the interior of the IAB. Bray et al. [1997] describe energetic westward-moving discrete throughflow eddies ("teddies") in the TOPEX/Poseidon sea surface height data in the IAB along 14°S. The teddies are most likely to occur during August-October when throughflow is maximum. The September 1995 WOCE CTD section across the IAB directly sampled one of the anticyclonic eddies, and the warm, fresh core suggested a source within the Indonesian interior seas. The westward migration suggests likely sources from a remotely wind-generated Rossby wave either in the equatorial Pacific [Clarke and Liu, 1994], although at 14°S the features have a phase speed of 0.19 m s^{-1} which is nearly twice as fast as a first mode baroclinic Rossby wave. The Rossby waves may be advected by the mean westward ITF as it enters the IAB. An alternative formation mechanism may be via instabilities caused by a fast-flowing current as it exits a strait, such as suggested for Mediterranean eddy formation by Prater [1992]. Further, it is not clear that the presence of the 60-day energy seen both in the pressure gauge data along the coastal wave-guide, and in the teddies of the IAB, is entirely coincidental. It could be that wind-forced Kelvin waves travel down the archipelago, impact the coastal sea-level signal, and subsequently modify the flow through the straits to generate intermittent eddies [Nof, 1995]. Ostensibly however, there is an 8 month lag between intraseasonal events that occur at Bali and events that occur in the IAB interior (14°S, 106°E), when theory predicts that a Kelvin wave should propagate from Bali to Timor in just 4-6 days and on to (14°S, 106°E) in just 5 months. Possibly the Kelvin wave signal may be obscured by locally forced changes in sea-level. The challenge will be to separate the remote and locally generated signals.

IMPACT/APPLICATIONS

The transport from the Pacific to the Indian Ocean through the Indonesian throughflow is a significant component of the thermohaline circulation and global heat budget. A better understanding of the transport and upper ocean properties of the region, such as achieved by the measurements reported here, will significantly improve our ability to understand and predict global and regional climate variations. The observations adequately resolve the mass and property variability on a variety of temporal and spatial scales, and will be instrumental in improving global and regional oceanic and coupled models.

The shallow pressure array has been well timed and positioned to measure the strong 1997-98 ENSO event and it's impact on transport of mass and properties in the throughflow. Little is known about interannual frequencies in the region, mainly because few long-term data sets exist with which to examine them. The pressure gauge network is due to be recovered in March 1999, and hence will not sample the effect of the current La Niña on throughflow transport. We have to date, been unsuccessful in attempts to fund the March 1999 cruise as another turn-around cruise for the sensors, and thus ensure sampling throughout the entire evolution of a El Niño and La Niña event in the throughflow region.

RELATED PROJECTS

This work is closely related to the Indian Ocean WOCE program, especially WOCE Hydrographic section I-10.

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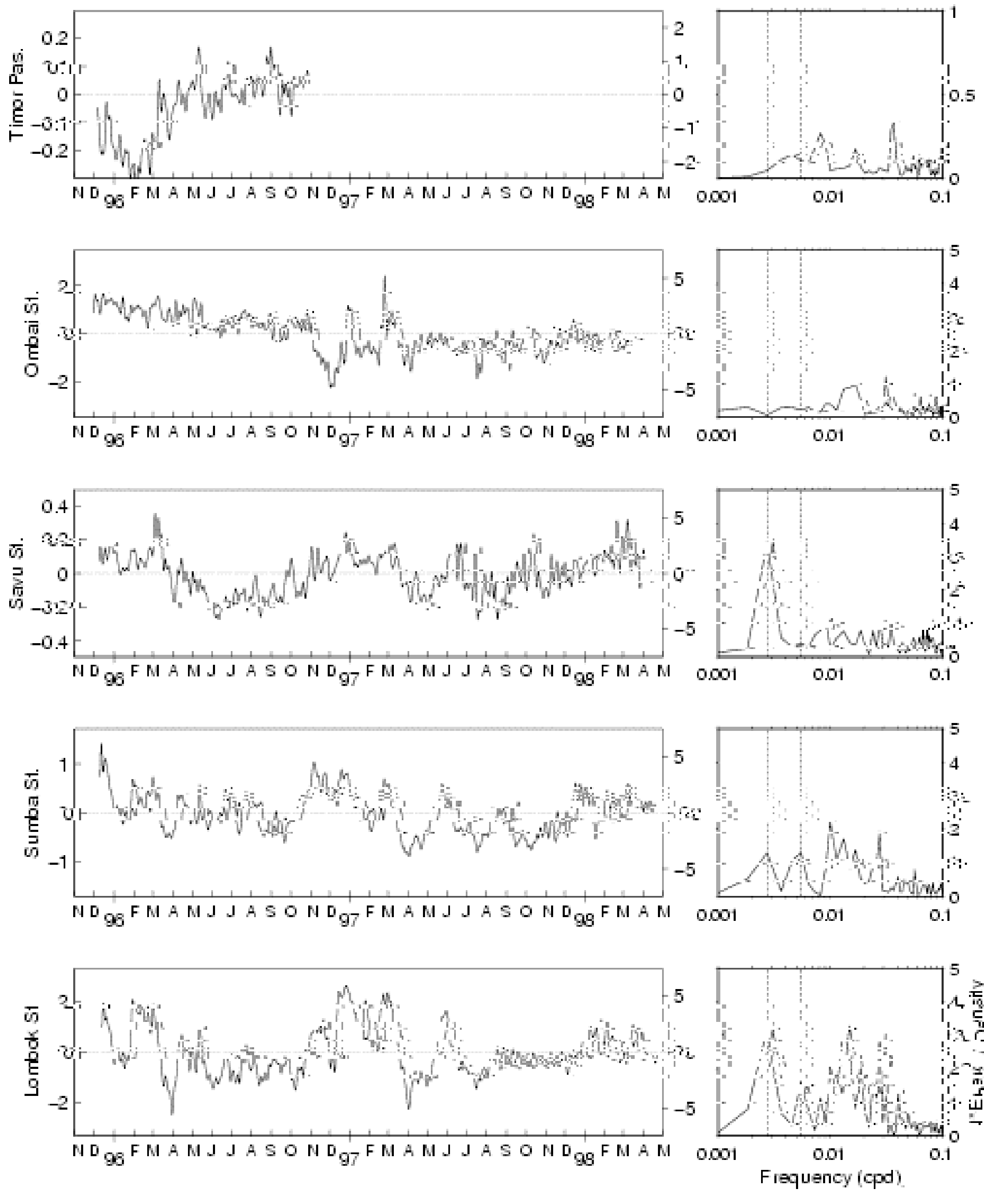

Figure 1: The cross-strait geostrophic surface velocity (m/s: left axis) and associated geostrophic transport (Sv; right axis) for the five straits monitored by the pressure gauge array.Geostrophic transport was estimated using an exponential decay in transport with a depth scale of 62 m. The energy-preserving spectrum for each strait is in the right panel, and the annual and semi-annual frequencies are marked. Note the changing scales on the vertical axis.